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THE TIDES OF AUSTRALIA

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1. Introduction

It was one of the many triumphs of Newton to demonstrate that the daily ebb and flow of the waters of the ocean, which we call the tides, are due to the gravitational attraction of the sun and the moon. From his theory the tide producing force on the waters of the earth at any point can be computed with precision for any given disposition of the sun and moon. At any place it can be resolved into a vertical and horizontal component. The vertical force, however, tending as it does to lift the water, amounts only to something of the order of a couple of grains weight per ton of water, which can produce no evident effect. It merely reduces the weight of the water to a very small degree and causes no horizontal motion. But the horizontal component of the tide-producing forces, although correspondingly small, can be effective in causing movement of the water in spite of its apparent insignificance. In the lower reaches of the Murray River the fall is only three quarters of an inch to the mile, which means that the force producing the motion of the seater is the resolved part of gravity down this almost level slope. This amounts to a force of about 185 grains weight per ton of water, and salt, little as it is, it is enough to cause the flow in the river. Small as this force is, however, it is about 80 times as much as the greatest horizontal forces producing the tidal movements throughout the oceans of the world. The tidal forces are very small, but they act all the time upon every of ton of water in the seas and we observe the concentrated effects around the coastal boundaries, where the rise and fall of the water is usually much greater than it is at a distance from the land. For example, Captain T.J.J. See of the United States Navy gives the mean value of the tidal range for island stations in the Pacific as 323 feet, whereas where the ocean laps the eastern shores of Australia the range of tide is about doubled. The enhanced range along the coastline is explained by the fact that as the tidal wave approaches the shores of a continent its energy is usually concentrated into shallower and narrowing inlets, although occasionally as in the case of Port Phillip we get a reverse effect. There the spring range at the heads is over 3 feet but, owing to the narrow entrance and the large area of the bay, the spring mange at Williamstown is only 3 feet.

Back to top

2. The Progressive Wave Theory

The tide-producing forces at any place on the earths surface undergo, of course, continuous variation owing to the revolution of the earth on its axis and to the movements of the sun and moon relative to the earth. These movements, however, though complex, are perfectly well known and it is still a practicable problem to compute exactly the magnitude of the tidal forces at

any place at any particular time. It is one timing however to be able to compute the tidal-producing forces and quite another thing to determine the effects which these forces produce upon the waters of the ocean. It would be possible to do this if the earth were covered by water of uniform depth or if the oceans of the earth were circular or rectangular or of some simple mathematical form and if the depth varied according to some simple law, but the actual shapes of the oceans are so exceedingly complex and the depths vary so erratically that in the present state of knowledge the calculation of the effects of the tidal forces is beyond our powers. Even now the fundamental problem as to the mode of origin of the tidal wave can hardly be regarded as definitely settled. The tidal wave is not a "free" wave, such as might be caused by a temporary disturbance, when the wave, once started, travels with a speed depending simply on the depth of water. In the case of the tides the generating forces are acting all the time and the theory of the first investigators, beginning with Laplace, was that the tidal forces set up what was known as a "forced" wave which necessarily travelled round the earth in a period harmonising with that of the forces. It would be easy to picture this happening in an ocean which covered the whole earth, but in our real world there is only one ocean in which a ware could possibly travel right round the earth and that is the Great Southern Ocean, though even in this ocean the passage for such a wave is seriously restricted between Cape Horn and Graham Land on Antarctica. The theory therefore that has been generally held by tidal investigators, from Laplace, Lubbock, Whewell and Airy onwards, is that the tidal wave, travelling round the world in the Southern Ocean, propagates its disturbance northwards into the Indian, Atlantic and Pacific Oceans in turn. This is commonly known as the Dynamic or Progressive Wave Theory. The 1936 edition of the **Oxford Advanced Atlas**, for example, in its map of co-tidal lines, shows an area of the Pacific Ocean west of South America marked "Origin of the Tidal Wave" and from this origin the wave is pictured as being propagated in a north-westerly direction into the northern half of the Pacific, and along the Southern Ocean, which is the source from which tidal waves travel, northward into the Indian and Atlantic Oceans. This is substantially the same assumption as is made by Whewell who drew the first map of the co-tidal lines of the world in 1836, and by Airy who followed him. Figure 1 is a reproduction of a part of a map of the world, showing co-tidal lines in the oceans surrounding Australia, published in 1926 in a treatise entitled "New Dynamical Wave Theory of the Tides" issued by the Hydrographic Office of the United States Navy and complied by Captain T.J.J. See, a vigorous champion of the progressive wave theory.

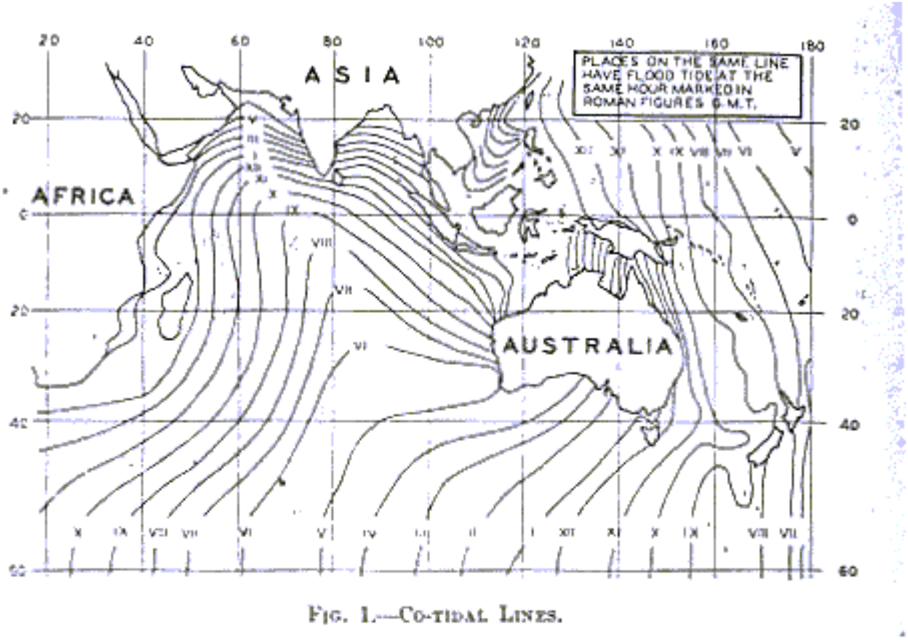

Fig. 1.—Co-tidal Lines.

From map by T. J. J. See, 1926.

The co-tidal lines show the onward march of the front of the tidal wave, it being high water at all points on the same co-tidal line at the one time. The co-tidal lines, drawn at hourly intervals, show the tidal wave approaching the eastern shores of Australia from the Pacific, then travelling

from east to west along the Southern Ocean, and from there flowing in a north-westerly direction across the Indian Ocean. It is obvious that in the making of such a map of co-tidal lines the imagination of the author has to be brought into play quite considerably, because we have no observations of the rise and fall of the water at points far out from land, and our actual observations, upon which the map of co-tidal lines is based, are confined to places on the shores of the continents and to islands. Now there are no islands in the ocean to the south of Australia and it follows that the shape of the co-tidal lines in that region in this map must be determined by the progressive wave theory which the author has in his mind rather than by actual observation.

There are serious difficulties to the acceptance of this simple theory of the progressive wave. Dr. G. R. Goldsbrough, for example, in a paper contributed to the Royal Society of London in 1928, showed by mathematical calculation that, in an ocean extending from the South Pole to latitude 45 degrees or less, only quite small semi-diurnal tidal waves can he generated in such depths as are comparable with the Southern Ocean. If however the Atlantic tides are derived from the Southern Ocean, the large semi-diurnal tides of the Atlantic clearly require that there should he large tides of a similar kind in the Southern Ocean. Moreover, although the tidal wave appears to travel in Atlantic from south to north it varies in height and speed in a way that is hard to understand if it is a simple progressive wave. If the phenomena of the tides along the south coast of Australia, for instance, are due to a tidal wave moving from east to west, how is it that from Cape Howe to the Head of the Great Australian Bight, more than half way along, we have a mean spring range of tide running from 5 to 6 feet, whereas from there on to Cape Leeuwin the range is only about 2½ feet? It cannot be explained either by a variation in depth of the ocean or by a change in its width. Again, going along the west coast of Australia from south to north, the tidal range at Springs from Cape Leeuwin up as far as Dirk Hartog Island is less than 3 feet but from there it increases rapidly until at Port Hedland it is 19 ft. 3 in. The progressive wave theory alone does not give us any reason able explanation of facts like these.

Back to top

3. The Resonance Theory of the Tides

There is another school of opinion that, at the beginning of the present century, was first firmly established by the work of Mr. Rollin A. Harris, then Chief of the Tidal Department of the United States Coast and Geodetic Survey. According to Harris instead of looking for a progressive wave travelling right round the globe, we should rather consider the oceans as great basins of water which are continuously subjected to the disturbing effects of periodic tide-producing forces. These may be divided out into forces of several different periods and the basin of water is capable of oscillating or setting up what is known as a stationary wave in many different ways. Out of all these many possible methods of oscillation there will probably be one or more that will keep time or nearly so with one or more of the tide-producing forces, which are continuously acting. If so, the water will naturally swing or oscillate in those ways which will keep time with the forces and those particular methods of oscillation will be emphasized and perhaps given a relative importance out of proportion to the forces which produce them. It is the same principle as that of resonance. So, if the ocean is capable of oscillating in some way periodic, say, with the lunar forces, it will do so and the corresponding tidal forces will produce an effect greater in comparison with the effects produced by other tidal forces than we should expect from our knowledge of their magnitudes. Thus the tide-producing forces due to the moon are about 2.3 times as great as those due to the sun, but we do not find that the lunar semi-diurnal tide is everywhere 2.3 times as great as the solar semi-diurnal tide. There are places around the coast of Australia where the solar tide is just is as big lunar tide and other places where there is five or six or even, as on the New Zealand coast, ten times as big as the solar. The most reasonable explanation of such effects that has been advanced is that they are due to the selective resonance of some adjoining body of water. If, for example, the solar semi-diurnal tide is much greater than we should expect, in comparison with the semi-diurnal tide due to the moon, the probable reason is that there is an adjacent basin of water that has a natural period of oscillation of just about twelve solar hours, which harmonizes with the period of the sun’s tide-producing forces. The repeated application of the tide-producing forces tests therefore to increase and

emphasize the wave due to those forces that have this particular period. Harris accordingly made the attempt to divide the oceans of the earth into areas which he calculated, from his knowledge of their shapes and the recorded depths, would oscillate in synchronism with one of the components of the tide-producing forces, and then he made a map of the co-tidal lines of the world, based of course as previous ones on actual observations of the tidal round the shores, but with an entirely different view point in the mind of the author, Harris' map, so far as it affects the oceans around Australia is reproduced in Figure 2, and it will be seen that the co-tidal lines, especially those to the south Australia, are altogether different in form to those in the map of Dr. See, who had at the back of his mind the idea of the progressive wave. In figure 1 the co-tidal lines to the south of Australia run pretty well north east and south west; in figure 2 they run roughly east and west. According to figure 1 the time of high water along the southern coast of Australia increases progressively as we go from east to west and it takes just over four hours for the tidal waves to move along the entire southern coast from Cape Howe to Cape Leeuwin, over about 35 degrees of longitude. On the other hand according to Figure 2, the tidal wave approaches the south coast of Australia from the south and it is high water at the west end of it at the same time as at the east end of it. It surely ought to be possible, one would think, to say defiantly which of these two views is correct. The south coast of Australia appears, according to this, to be in the position of being able to give decisive evidence for one side or the other. It is not however quite so simple as it may seem to form a definite opinion because, at most of our ports where observations are systematically recorded, the tidal wave has taken a considerable time to reach there from the open ocean.

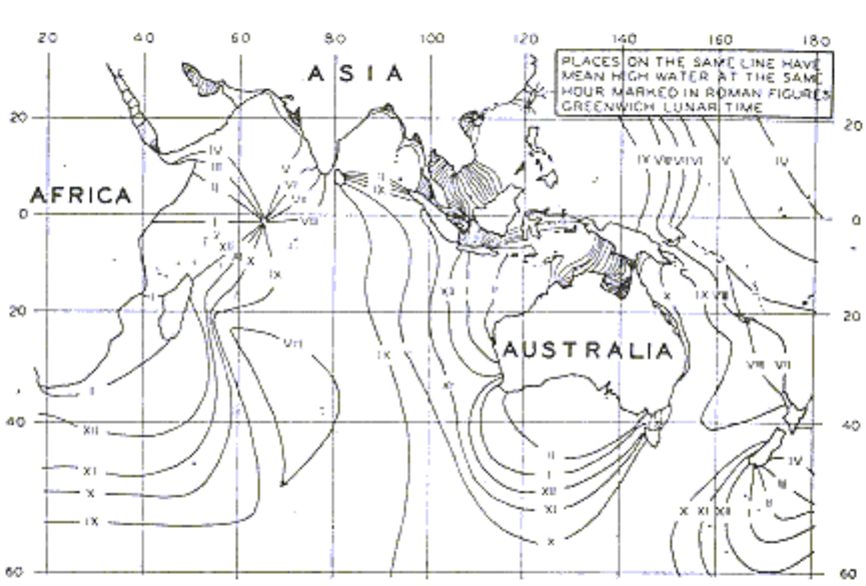

FIG. 2.—CO-TIDAL LINES.

From maps by R. A. Harris, 1904.

The tide, for example, takes over six hours to travel up the comparatively shallow water of Spencer Gulf., in South Australia, from the entrance up to Port Augusta at the top. It takes over three hours to traverse the shoals and channels of Port Phillip Bay from the Heads to Williamstown. Obviously we must consider only ports close to the open ocean to reach which the tidal wave has not been forced to move over long stretches of shallow water. The pamphlet on "South Australian Tide Tables for 1938" issued by the South Australian Harbours Board gives the times of high water on full and change days at a number of ports along the coast. Taking the most easterly and the most westerly of these, Port Macdonnell, close to Cape Northumberland, and Port Eyre, near the head of the Bight, the time of high water is given as practically the same at both places, Port Macdonnell being two minutes later than Port Eyre. These ports are separated by about 8 degrees of longitude, so that according to the co-tidal lines of Figure 1 we should expect Port Eyre to be about one hour later than Port Macdonnell. Again the Tide Tables issued by the Victorian Ports and Harbours Authorities give a list of tidal differences with reference to Williamstown as a standard port for various ports both in Victoria and other States,

and they give the time of high water at Springs at Port Macdonnell as about 27 minutes earlier than at Warrnambool which has over 2 degrees of longitude to the east of it. The time given at Port Campbell, which lies still further to the east, is with in two minutes of that at Port Macdonnell. The Admiralty Tide Tables give a list of tidal differences for many ports along the Australian coast and they show the tide at Eucla Roads to be two and a half hours earlier than that at Port Eyre which has 3½ degrees of longitude to the east, and, on the far-western side of the southern coast, the tide at West Cape Howe is from two to three hours earlier than at any one of six ports between that and Eulca from which records have been obtained. In the **Manual of Tides** by Rollin A. Harris, published by the United States Coast and Geodetic Survey, a table is complied giving the co-tidal hour for high water at spring tides, that is the number of lunar hours between the time of high water at the place and the last transit of the moon at Greenwich, for a large number of ports on all continents. The following list is taken from the table, for places on the southern coast of Australia, in order running from east to west.

Station	Co-tidal hour	Station	Co-tidal hour
Port Fairy	3.02	Denial Bay	3.90
Portland Bay	3.05	Port Eyre	3.17
Port Macdonnell	2.65	Eucla Roads	2.11
Rivoli Bay	3.18	Esperance Bay	4.03
Kingston	2.78	King George Sound	2.81
Victor Harbour	3.86	West Cape Howe	0.85
Streaky Bay	3.13		

Instead of showing a progressive increase from east to west the table shows only inch variations as might be expected front differing local conditions . According to the co-tidal map of Figure 1 there should be a gradual increase in the co-tidal hours in this list of about three hours from top to bottom, but nothing of the kind is shown. The evidence seems to be definitely against the theory of the tidal wave moving from east to west along the Southern Ocean to the south of Australia. On the other hand it shows that the front of the tidal wave approaching the southern Ocean must be in a general way approximately parallel to the shore.

The two co-tidal maps show that the northern coast of Australia is affected by tidal waves which approach it both from the Indian Ocean at the western end and from the Pacific on the east. These two tides mingle in the waters to the north of Arnhem Land. In Van Dieman Gulf at rising tide a stream setting eastward enters the Gulf from the north through Dundas Strait where it meets a stream setting eastward which enters through Clarence Strait. Yet along the north shore of Arnhem Land the flood stream is in the main towards the east.

Back to top

4. Tidal Ranges round Australia

The range of tide along the northern coast of Australia is much greater than along the southern coast. From Torres Strait round to the western end of the coast of Arnhem Land the spring range is about 10 feet, falling a little to 8½ feet at Port Essington, but increasing as we go westward until at St. Asaph Bay on Melville Island the range is 14 feet. At Port Darwin the mean spring range is increased to 24 feet but it is sometimes as much as 30 feet. Further along, at Wyndham, at the western end of the apex of the Cambridge Gulf, it is 23 feet, and further along still, at Collier Bay, and Kings Sound, where we have by far the biggest tides of Australia, the spring range is as much as 36 feet in Collier Bay with a mean spring range of 34 feet at Derby. Going further west the spring range gradually diminishes until we get to North West Cape. It is 28 feet at Broome, 19 ft. 3 in. at Port Hedland where a self registering tide gauge has been established, 18 feet at Cossack and 13 ft. 6in at Fortescue. To the south of the Northwest cape the spring range of tide becomes very much less. It is only 6 feet at Maud Landing, just to the south of it, 5 feet at Carnarvon, and at Geraldton it is only 2ft. 6in. From here on, to the south as far as the Leeuwin and along the western end of the south coast as far as Eucla, the range is only 2ft. 6in. or less

and we have along this corner of the Australian coast the smallest tides in all Australia. Going further to the east along the south coast the range increases. It is 5ft. 6 in. at Port Eyre, 6 feet at Streaky Bay, Coffin Bay, Port Lincoln and at Cape Willoughby, on the eastern end of Kangaroo Island. The range, of course, increases beyond this as the tidal wave moves up the gradually narrowing Spencer and St. Vincent Gulfs. Further along the ocean coast it is 5 feet at Port Macdonnell, but diminishes to 3 feet at Portland and Warrnambool, and then increases again, being 5 feet at Apollo Bay and 5ft.3in. at Port Phillip Heads. It is 8 feet at the entrance to Corner Inlet, but only 3 feet at Lakes Entrance and at the mouth of Snowy River. At Gabo Island the mean spring range is 6 feet and it stands at around about 6 feet all up the east coast as far as Wide Bay, at the southern end of Great Sandy Island off the Queensland coast. It is 5 feet at Jervis Bay, 6 feet at Sydney Heads, diminishing to 5.1 feet at Fort Denison, within the Harbour 5.5 feet at the entrances to the Clarence Richmond Rivers, and 6.6 feet at the Brisbane bar. From here on, going north, the range increases. It is 11 feet at the entrance of the Mary River, 12 ft. 6 in. at Sea Hill, Keppel Bar, and at Broad Sound, where the rise at springs at different points in the Sound may be from 24 to 30 feet. the range being the greatest on the eastern coast. The **Australia Pilot**, issued by the Admiralty says "In Broad Sound, the flood streams from northward and southward meet, thus producing the great range of tide here found". Doubtless this is accentuated by the configuration of the bay and the shallowing water. From there on, going further north, it diminishes again being 16ft. 7 in. at the Flat Top Island Anchorage, Mackay, 7ft. 9 in. at Townsville, 6ft. 5in. at Cairns, 6ft. 3in. at Cooktown and 10 feet at Cape Grenville, just south of Cape York.

Along the shores of Tasmania the highest tide is along the northern coast where the spring range is about 10 feet at Stanley, Devonport, and Port Dalrymple, and at Roden and Hummock Islands in the Furneaux group at the eastern end of the north coast. At Hobart the mean spring range is 4 ft. 6in. and at Macquarie Harbour, on the west coast, it is about 3 feet.

Back to top

5. Variations due to local conditions

A certain amount of this variation in the recorded heights of tides may be bought about by the narrowing and shallowing of the channel along which the tidal flood stream progresses. If the tidal wave enters a gulf which gradually contracts in width and decreases in depth the energy of the wave is spread over a continually diminishing area and the height of the wave is increased. There is a very good example of this in the behaviour of the tidal wave as it proceeds up the Spencer and St. Vincent Gulfs in south Australia. As we have already seen the tidal waver reaches Port Macdonnell, near the Victorian border, and Port Eyre, near the head of the bight, at about the same time. It takes three hours and twenty six minutes to traverse Investigator Straight and Backstairs Passages, separating Kangaroo Island from the mainland, to reach Rapid Bay, on the eastern side of the entrance to St. Vincent Gulf and a point near Sturt Bay on the other side. At Rapid Bay the mean spring range is about 6 feet. The wave at this stage starts to travel much faster in the deep water in the middle of the Gulf than it does in the comparatively shallow water at the sides, with the result that the wave front becomes more and more curved as it proceeds, being much more advanced at the centre that it is at each side. The consequence is that by the time it reaches the head of the Gulf, having traversed a distance a little short of 100 miles from the entrance, it is practically parallel to the coast line all the way round and high water reaches the Semaphore, which is on the shore of the Gulf alongside Port Adelaide, Black Point on the western side of the Gulf, and Port Wakefield at the head of the of the Gulf, at the same time, one hour and twenty minutes after Rapid Bay. Moreover as the wave proceeds up the narrowing Gulf it increases in height, the spring range being 6 feet at Rapid Head, 8 ft. 3 in. at Port Adelaide, and at the head of the Gulf, at Port Wakefield, the range is 11 feet. Similar phenomena take place in Spencer Gulf to an even more marked degree, for it is about double the length and contracts to a narrower width. The tidal wave takes six and a half hours to go from Thistle Island, at the mouth to Port Augusta, at the head and the spring range increases from 5 feet at Thistle Island to 12 feet at Port Augusta.

At Port Lincoln, on the western side of the entrance to Spencer Gulf, the peculiarity of the tidal behaviour was noted by Flinders. He observed there that the tides did not exceed 3½ feet and that, as in Princess Royal Harbour, there was only one high water in 24 hours, which took place at night, about eleven hours after the moon's passage over the meridian. Yet at Thorny Passage, which is but a few leagues distant, there were two sets daily. The difference in so short a space appears extraordinary; but it may perhaps be accounted for by the direction of the entrance to the port, which is open to the north-east from whence the ebb comes (Captain Flinders, Terra. Aus., Vol. 1, pg 150). The explanation here offered is by no means obvious as it stands, but taken in conjunction with another well - marked characteristic of our tides it gives us the solution. All round the Australian coast there is a well marked "diurnal inequality" as it is termed; that is to say, the for noon and afternoon tides are not of equal height, but one may be much higher than the other. At Port Lincoln the observable daily tide is simply the higher one of the two daily tides, for owing to the direction of the outlet of the harbour the water cannot escape freely, as the ebbing tide from the Gulf retards its outward flow. The result is that the level of the water in the large area of the Port Lincoln Harbour falls very slowly, so slowly that the second and lower tide which follows in the course of the day does not appreciably raise the level of the water, and so is not apparent as a tide.

Back to top

6. Diurnal Inequality

This phenomenon of diurnal inequality, so evident at Port Lincoln, is a marked characteristic of Australian tides generally. Curiously enough, in the waters of the North Atlantic, where the tides were first studied, there are at most ports two equal tides a day and they are at regular time intervals apart, so that when the exploration of distant seas showed in many cases that the two waters or the two low waters or even both were unequal in height the occurrence was at first thought to be something abnormal. Yet the theory as to the cause of the tides shows that diurnal inequality is something that is to be expected whenever the sun or moon is not on the equator, especially at places on tire earth in high latitudes, and that the remarkable thing is, not that it occurs around the coasts of Australia and other places, but that it does not occur in the North Atlantic. When, for example, the sun is north of the equator, it tends, at a point in the southern hemisphere, to cause the evening tide to be higher than the morning tide, but when the declination of the sun is south the effect is reversed. This happens at Port Adelaide, South Australia, a place where the sun has a pronounced influence on the tides. At this port there is a definite diurnal inequality which changes sign about the equinoxes. The maximum difference in height of the two daily tides is about 3 feet, with a mean range of 8 ft. 2 in., and the inequality changes sign a little before the first equinox and a little after the second. That is to say from about the middle of October until about the middle of February the morning tide is the higher, the sun being then south of the equator, but from then on to the middle of October again the afternoon tide is higher than the morning tide. In this instance the sun is the dominating influence and there are few where this is the case. At most ports the moon exerts the chief controlling force and the moon's declination changes sign about every fortnight, so that usually the changes in sign of the diurnal inequality are much more frequent. Generally for one-half of every month the sun and moon will combine to give a diurnal inequality of the same kind but their influences in this respect will be in opposition for the other half of the month.

Back to top

7. Harmonic Analysis

It is evident that the combination of a number of simple waves may result in a wave motion that is anything but simple, and it has been demonstrated mathematically that any wave motion whatever, provided that it is periodic, may be resolved into a number of simple sine waves. This is done in what is known as the Harmonic Analysis of the tides. The tide producing forces all acts over recurring periods which are definitely known. The resultant action can therefore be resolved into a number of simple waves each such as might be produced by a fictitious satellite moving round the earth in a circle on the equator. Each one of these simple waves is referred to as a "component". At most places the two principle ones are the semi-diurnal waves caused by the

sun and the moon as the earth resolves on its axis. They are generally known as tidal literature as S_2 and M_2, the suffix 2 indicating that they are semi-diurnal and the letters S and M indicating sun and moon. These are simple regular waves such as would be caused if the sun and the moon were always at the same distance from the earth and always on the equator. The period of S_2 or the time interval between one high water and the next is twelve hours and that for M_2 is twelve hours and 25 minutes. These periods are such that at intervals of about a fortnight they are both acting to produce high water at the same time, when the spring tides are the result, and midway between these times they are acting in opposition, one causing high water at the same time as the other by itself would cause low water so that the water rises at an amount of equal to their difference only and neap tides are observed.

To take account of the moon's declination we must introduce a diurnal wave to give the observed diurnal inequality. The moon's declination, however is not constant. It varies from a maximum declination north to a maximum declination south or **vice versa** in an average period of 13.66 days. The difference between the tide producing forces at the two daily high waters, which is the cause of diurnal inequality, is greatest when the moon has its greatest declination and gradually reduces to nothing as the moon moves on to the equator. This effect may be regarded as equivalent to that of two diurnal waves of equal height, having an average period of 24 hours 50 minutes, double that of M_2, of such lengths that they act together at intervals of 13.66 days and are in opposition at intervals midway between, giving then the equivalent effects of the moon on the equator. Just as the combination of the lunar and solar semi-diurnal tides gives the impression of a single semi-diurnal tide that varies in height from springs to neaps so the resultant action of these two diurnal waves would be that of a single diurnal tide varying in height from a maximum when the moon has its greatest declination to a minimum when the moon is on the equator. These two diurnal tides, which take account of the varying declination of the moon, are generally denoted by the letters K_1 and O_1, the suffix 1 denoting that the tide is diurnal. The influence of the more slowly changing declination of the sun is similarly equivalent to the combined effect of two equal diurnal waves which are in opposition at the equinoxes and act together at midsummer and midwinter when the sun is furthest from the equator. One of these has the same speed as K_1 so that the two are combined together. Thus it may be considered that the changing declinations of the sun and moon set up three diurnal waves usually denoted by the letters O_1, P_1 and K_1. O_1 is known as the lunar diurnal. P_1 as the solar diurnal, and K_1 common to both sun and moon, is known as the luni-solar diurnal. These three waves will be equivalent in effect to that of the varying declinations only to a first approximation. We should need a long series of such waves, gradually diminishing in amplitude to make the equivalence exact. But these three will be by far the largest in the series.

Again the variation in the moon's tide producing force by reason of it continually changing distance may be regarded as the equivalent of another component wave. The moon describes its elliptic path around the earth, with an eccentricity of about one twentieth, in an average period of 27.55 days. When it is nearest to the earth, in perigee, its wave producing power is greater than when it is furthest from the earth, in apogee. If now we introduce another semi-diurnal component such that at perigee its high water will synchronise with M_2 and at apogee it will produce low water at the same time as M_2 will cause low water, the effect of the new component on M_2 will be to increase its height at perigee and decrease it at apogee, corresponding to the effect of the varying distance. In other words we may regard the eccentricity of the moons orbit as setting up this additional tidal wave. The principle component tidal waves are therefore:-

M_2 Principle lunar semi-diurnal
S_2 Principle solar semi-diurnal
N_2 Lunar elliptic
K_2 Luni-solar semi-duirnal
K_1 Luni-solar diurnal

O_1 Lunar diurnal
P_1 Solar diurnal

To get complete mathematical equivalence we require a very long series of components, but these seven are the most important ones, and the character of the tides at any place is determined by their relative magnitudes and phrases.

The period of each one of these component waves is known from the movements of the sun and moon. With this knowledge it becomes possible, by the method of 'harmonic analysis' given the records of a self registering tide gauge over a considerable period, to determine the magnitudes of all the components waves and their relative phases at the beginning of the period. The length of time over which the records must extend for successful analysis may be a month or even a fortnight but more accurate results are obtained if the observations are complete over a full year. Once the magnitudes of the components are found and their phases at any particular time, it is a simple matter to compute their combined effect at any time afterwards. This is the only system of tidal prediction that is of any value for the Australian tides. Before it was introduced by Lord Kelvin, then Sir William Thompson, in 1867, the tides at Australia ports were a hopeless puzzle. Now at the principle ports predictions are issued for a year ahead by using the constants determined by harmonic analysis. Lord Kelvin made the first application to Australian tides by analysing records of the Fremantle tides in 1878 (**Nature**, Oct. 1878). At Port Adelaide the tides are still being predicted with success from constants found from the analysis of two separate years records made over 40 years ago.

Of recent years our knowledge of Australian tides, particularly along the northern coast has been greatly extended by investigation made by the Hydrographic Department of the Australian Navy. The following table gives the amplitude in feet, that is half the wave height, of each of the seven principal components at a selected number of places round the coast where analyses have been made. The places are ranged in order, beginning near Cape York and going round Australia anti-clockwise. Authorities are given by references at the end of table.

Back to top

Place	**Amplitudes of Component Waves in Feet**						
	M^2	**S^2**	**N^2**	**K^2**	**K^1**	**O^1**	**P^1**
Frederick Point[1] 10° 43' S, 142° 35' E	1.8	1.6	0.8	0.4	1.6	0.7	0.5
Tuesday Island[1] 10° 33' S, 142° 21' E	1.6	1.6	0.7	0.4	2.0	0.7	0.7
Thursday Island[1] 10° 35' S, 142° 13' E	1.2	1.1	0.5	0.3	1.9	1.0	0.5
Proudfoot Shoal[1] 10° 31' S, 141° 29' E	2.2	0.5	0.4	0.1	1.7	1.0	0.6
Port Langdon, Groote Eylandt[2] 13° 52' S, 136° 50' E	0.85	0.41	0.28	0.11	0.50	0.56	0.16
Cape Don, Coburg Peninsula[2] 11° 18' S, 131° 46' E	1.98	0.85	0.38	0.23	0.82	0.65	0.27
Camp Point, Melville Island[2] 11° 36' S, 131° 25' E	3.39	1.50	1.12	0.40	1.52	1.00	0.5
Cape Hotham[2] 12° 03' S, 131° 17' E	3.97	1.61	0.84	0.43	1.15	0.75	0.38

Tower Beach, Bynoe Harbour[2] 12° 35.2' S, 130° 34' E	5.64	2.95	1.06	0.80	2.03	1.02	0.68
Port Darwin[3] 12° 38' S, 130° 51' E	6.56	3.44	1.04	1.02	1.91	1.14	0.44
Port Hedland[4] 20° 22' S, 118° 36' E	5.51	3.35	0.87	0.80	0.79	0.50	0.19
Beadon Point[2] 21° 38' S, 114° 06.5' E	1.88	0.98	0.30	0.27	0.62	0.40	0.21
Fremantle[4] 32° 03' S, 115° 45' E	0.12	0.11	0.03	0.03	0.42	0.32	0.12
Princess Royal Harbour[5] 35° 08' S, 118° 00' E	0.16	0.26	0.07	0.07	0.62	0.42	0.17
Adelaide[6] 34° 51' S, 138° 30' E	1.70	1.68	0.09	0.46	0.83	0.52	0.22
Williamstown, Victoria[5] 37° 52' S, 144° 54' E	0.81	0.10	0.09	0.03	0.29	0.22	0.10
Sydney, Fort Denison[5] 35° 52' S, 151° 12' E	1.62	0.40	0.35	0.12	0.47	0.30	0.13
Newcastle[5] 32° 57' S, 151° 44' E	1.60	0.39	0.35	0.13	0.51	0.29	0.15
Ballina, Richmond River[5] 28° 52' S, 153° 33' E	1.08	0.28	0.20	0.07	0.45	0.31	0.14
Brisbane[5] 27° 20' S, 153° 10' E	2.22	0.62	0.42	0.18	0.70	0.39	0.21
Cairns[5] 16° 55' S, 145° 47' E	1.96	1.12	0.66	0.30	0.87	0.41	0.29
Cooktown[5] 15° 28' S, 145° 10' E	1.87	0.79	0.45	0.21	0.29	0.30	0.10

Authorities. - [1] Report on tides, Currents and Tidal Streams in the southern part of Torres Strait, 1931, Hydrographic Department, Admiralty. [2] Supplied by the Hydrographic Department, Australian Navy. [3] R.W. Chapman and Captain Inglis, A.A.A.S. Reports, Vol. 9, p. 67, 1902. [4] H.B. Curlewis, Proc. R.S. of W.A., Vol, I, p. 28, 1915. [5] Admiralty Tide Tables, Part 2 and also Special Publication No. 98 of the U.S. Coast and Geodetic Survey. [6] R.W. Chapman and Captain Inglis, A.A.A.S. Reports, Vol. 7, 1898.

Back to top

8. Explanation of Peculiarities of Tides from Results of Harmonic Analysis

A study of the preceding table will give a better understanding of the nature of the tides around the Australian coastline than any general description can possibly do, for it is on the relative magnitudes of the component waves that the idiosyncrasies of the tides depend. Consider for example the two principal semi-diurnal components M_2 and S_2 due respectively to the moon and the sun. As we have seen we might expect from a comparison of the title producing forces that M_2 would lie more than twice as great as S_2. This is so in a number of cases but the ratio between the two is anything but constant, and there are six instances on the list, Frederick Point, Tuesday and Thursday Islands, in the north, and Fremantle, Princess Royal Harbour and Port Adelaide, in the south, where the two are practically equal. At Princess Royal S_2 is even greater

than M_2. At spring tides the range, due to the semi-diurnal waves, is 2 (M_2 + S_2) and at neaps, if the two are equal or near equal, they practically neutralise one another and cause no rise nor fall at all. This is what happens at Port Adelaide where at this period the recording gauge shows frequently little or nothing in the way of tide, in some cases the level of the water remaining almost constant for a whole day; in other cases one small tide occurs during the day. On each side of this tide is markedly irregular both as regards and height, and the apparent impossibility of saying when the tide will be at this particular period has presumably gained for it its name as "The Dodger". The further we get away from the neaps the more regular is the tide, until at spring tide it is fairly normal. The reason for this is that at the neaps the semi diurnal tides are practically eliminated and the rise and the fall of the water is then controlled by the diurnal tides which give only one tide a day and are relatively large K_1 having an amplitude about that of M_2 or S_2. At Princess Harbour and at Fremantle similarly the sun has as great effect as the moon and the semi diurnal waves balance one another out at the neaps. The range of tides at both places is small and the diurnal tides are relatively large compared to S_2 and M_2. Thus at Fremantle the amplitude of K_1 is 0.42 and O_1 is 0.32 compared with 0.12 for M_2, and at Princess Royal Harbour K_1 is about four times as big as M_2 and O_1 is more than twice as great. The consequence is that over most of the month the diurnal components the situation and there is evident only one observable tide in the 24 hours.

The peculiarity that the sun has a much bigger effect upon the tides in comparison with that of the moon would then be expected from the calculation of the relative tide producing forces seems to hold good right round the coastline from Adelaide to Fremantle. The explanation given by Rollin A Harris was that this was due to the fact that the body of water to the south of Australia, lying between it and Antarctica has a depth such that its natural period of swing, about a line running east and west through the middle of it, is exactly twelve solar hours. A standing wave or continuous oscillation of this ocean is thus set up, keeping time with the sun , producing thus a much greater effect than other predictions forces that meet with no such harmonious response. More recent work has shown that this kind of oscillation of the water is not the way in which the water is likely to swing on a rotating earth, but nevertheless in a general way the explanation probably remains good, that the effect is due to the resonance of the Southern Ocean to these particular periodic forces.

At the time when this dominating influences of the sun was first made known by the analysis of the tides at Port Adelaide nothing corresponding was known elsewhere except at a port in the Gulf of Mexico. But since then the work of the Hydrographic Department of the Admiralty has shown that at the opposite corner of Australia, at Tuesday and Thursday Islands in the south of Torres Strait the same phenomenon occurs. There again the diurnal tides are greater than the semi-diurnals with the result that diurnal inequality is always very marked and there is apparently extraordinary irregularity at and near the period of neaps. Tidal curves for successive days on Tuesday Island illustrate how the sun controls the situation, for high water comes at almost the same hour day after day; at Thursday Island similarly there is nothing approaching the advance in time of 50 minutes a day common in other places. Our Australian sun certainly has a great influence on the land but few would expect this to extend to the surrounding waters.

At Port Headland, on the north-west coast, we have a very different state of things. The table shows that the amplitude of the lunar semi-diurnal wave is 5.51 and that of the corresponding solar wave is 3.35, more in accordance with the tidal forces, and the amplitude of the largest of the diurnal waves , K_1 is only 0.79. The spring range is here over 19 feet and as the neap range is generally over 4 feet it follows that the diurnal waves, the total range of which when all three are acting in unison is less than 3 feet, can never have the effect of changing the semi diurnal character of the tide. All that the diurnal waves do is to cause an inequality in the two daily tides that amounts to a maximum of about 2 feet when the moon has its greatest declination. Here undoubtedly it is the moon that is the more potent influences and not the sun. Each day high water occurs about 50 minutes later than it did on the day before as it is normal behaviour where

the tide follows the moon, and it is one of the few ports in Australia where the old method of predicting the time of high water, from a knowledge of the interval of time elapses between high water and the last transit of the moon across the meridian, can be applied with even approximate accuracy. The "establishment" at Port Hedland, that is the interval of time between high water and the moon's transit, ranges between nine and one-quarter and twelve hours, following a very regular curve depending on the time of the moon's transit. No such regular curve applies however at places like Port Adelaide and Thursday Island where there are not the same number of tides in a month as there are transits of the moon.

Further along the northern coast, at Port Darwin, where there is a spring range of 24 feet, it will be seen from the table that the analysis is very similar to that for Port Hedland, the dominant waves are M_2 and S_2, and M_2 is nearly twice as great as S_2, so that again the moon is in control, but in this case the diurnal tides are relatively more important. If we add together K_1,O_1 and P_1 we get 3.49 as the amplitude or, say, 7 feet as the range of the resultant wave when all are acting in unison, which may be greater than the neap range due to the semi diurnals M_2 and S_2, so that we might expect occasional strange behaviour at this period. There are two tides a day, however, throughout the month but the diurnal inequality is very great especially in the low waters. The greatest effect occurs in December and January, when the two high waters may differ by 4½ feet and the two waters by as much as 9 or 10 feet. But sometimes in March and April, when the moon is from 8 to 10 or from 20 to 24 days old, two amalgamate to form one long high water. When approaching this stage the two high waters get more and more nearly equal and the two low waters more unequal until at last the H.L.W is equal in height to the two high waters on each side of it. At other times occasionally in September and early October the low high and the high low become of the same height and merge into one.

Speaking generally, as we proceed along the north coast from west to east, the range of the semi diurnal components gets less while the range of the diurnal waves remains more nearly constant. the result is that at the eastern end the tides , as at Tuesday Island, are chiefly diurnal but at the western end of the coast the semi-diurnal components are the controlling forces and there are two tides a day throughout the month.

Along the east coast, at Sydney, Newcastle and Brisbane, M_2 is about four times as great as S_2, so that along this part of the coast the moon has a greater effect, relative to the sun, than might have been expected. The diurnal tides are sufficient all the way along the coast to give a pronounced diurnal inequality to the daily tides but they are not big enough, relative to M_2 and S_2 to change the semi diurnal character of the tides even at neaps, except at Cairns.

Back to top

9. Tidal Records

The responsibility for the keeping of tidal records lies with the State Governments who have generally vested it in the local Harbours and Marines Board Authorities. Unless a special series of observations is taken for the purpose, as is often done by the Hydrographic Department of the Australian Navy, it is only the records of self recording tide gauges, which give a continuous trace of the level of the water, that are of any value for tidal analysis in these waters where the diurnal elements play such a prominent part. Such gauges have so far been set up only at important ports, as will be seen from the following table:-

NUMBER OF SELF-RECORDING TIDE GAUGES

State	Number of Gauges	Places where Fixed
Queensland	2	Brisbane, Cairns

New South Wales	6	Ballina (Richmond River), Clarence River, Newcastle, Sydney (2) Wollongong *
Victoria	2	Williamstown and Point Lonsdale
Tasmania	1	Hobart
South Australia	5	Port Adelaide, Port Pirie, Thevenard, Franklin Harbour (Cowell) and Whyalla*
Western Australia	4	Albany, Bunbury, Fremantle and Port Hedland
Northern Territory	1	Port Darwin

* At Wollongong and Whyalla gauges are established temporarily and will be moved on to other places when a sufficient length of record has been obtained to determine the tidal constants.

10. Tidal Predictions

For Ports where the tidal records have been subjected to harmonic analysis the Harbours Boards of Australia find it most convenient and economical to have their predictions made out on one of the tide predicting machines of England or America. Tidal predictions made out in this way are published in the Admiralty Tide Tables for each year for the ports of Thursday Island, Port Darwin, Port Hedland, Port Adelaide, Port Phillip (Point Lonsdale) Sydney (Fort Denison), Newcastle and Brisbane Bar , and the United States Coast and Geodetic Survey in their annual tide tables for the Pacific and Indian Ocean give predictions for Sydney, Melbourne (Williamstown), Port Adelaide and Port Hedland. In addition the Harbours Authorities in Victoria issue an annual pamphlet giving tidal predictions for the year for Williamstown and Port Phillips Heads, South Australia does the same for Port Adelaide, Western Australia for Port Hedland, and Queensland for Brisbane. In each of these cases tidal differences are given to permit of a reasonable estimates of the time of high water at other ports in the state. In Tasmania tide tables are issued by the Mersey and Launceston Marine Boards for their respective ports, but these are not based upon harmonic analysis.

The author wishes to express his obligations to the Hydrographic Department of the Australian Navy, to Mr. Curlewis, Government Astronomer at Perth, and to the various Marine Boards and Harbours Authorities for generous assistance in gathering information.

Back to top

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